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Analytical Investigation of Critical MHD Phenomena

Annual Report: September 1980—September 1981

STD Research Corporation

September 1981

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-202

for
U.S. DEPARTMENT OF ENERGY
Fossil Energy
Office of Magnetohydrodynamics

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Washington, D.C. 20545
Under Interagency Agreement DE-AI01-77ET10769

CONTENTS

ANALYTICAL INVESTIGATION OF CRITICAL MHD PHENOMENA

NASA Contract DEN3-202

Annual Report for the
Period 15 September 1980
to 30 September 1981

OBJECTIVE

The purpose of this effort is to investigate the critical phenomena that occur in open-cycle, coal-fired MHD topping cycle components. Among the phenomena to be investigated are transient phenomena, multidimensional phenomena, end effects, nonequilibrium effects, channel and slag phenomena, effects of generator inlet flows characteristic of coal-fired MHD combustors, gasdynamic and plasma nonuniformities and high microscopic Hall parameter phenomena, and additional phenomena and interactions as they are uncovered.

PROJECT HISTORY AND BACKGROUND

STD Research Corporation, founded in 1964, has been working since that time (18 years), both analytically and experimentally, in the field of multimegawatt open cycle magnetohydrodynamic (MHD) power generators for both military and civilian applications. This work has included a number of projects leading to understanding, predicting, and controlling the complex physical mechanisms that influence and affect the performance of advanced MHD power generation systems. Work in this field has led to the development of computer codes and models which permit the analysis and synthesis of components, subsystems and systems of complete MHD power plants. STD Research Corporation personnel trained in the application of these computer codes have made numerous contributions to the MHD field.

Contract DEN3-202 is a continuation of STD Research Corporation's participation in the U. S. National Program for the development of coal-fired MHD power generation. This participation began almost at the inception of the program with U. S. Department of the Interior, Office of Coal Research Contract OCR-14-32-0001-1211, dated 15 April 1971. The work was continued under Energy Research and Development Administration (ERDA) Contract E(49-18)2001, dated 31 March 1975, and U. S. Department of Energy (DOE) Contracts EX-76-C-01-2243 (transferred from ERDA), dated 15 March 1976, and AC-01-79-ET15501, dated 9 February 1979.

In September of 1979, program management for the STD Research Corporation work was transferred to NASA Lewis Research Center. Under NASA Contract DEN3-179, STD Research Corporation performed detailed analyses of the "as-built" specifications of the U. S. channel for the U-25 facility and the Arnold Engineering Development Center (AEDC) High Performance Demonstration Experiment (HPDE). Key findings were that (1) due to low wall temperatures, the predicted electrode voltage drops were many times larger than those used in the original design of both channels, and (2) the severe start-up Hall voltage transient predicted during Contract EX-76-C-01-2243 for the full-power design conditions of the HPDE were expected to be significant during the early testing phases as well. Post-test analyses of the MI-006-XXX series of HPDE tests confirmed these predictions. Parametric studies of HPDE performance showed that elevated wall temperatures could significantly improve the prospects for achieving the HPDE performance goals. Ancillary studies investigated effects of alternate channel cross sections, end effects, Faraday short circuits, scale dependence of transient phenomena, and other effects.

NASA Contract DEN3-179 was completed in July 1980. As the result of a competitive procurement, NASA selected STD Research Corporation in September 1980 to perform Contract DEN3-202, "Analytical Investigation of Critical MHD Phenomena."

In parallel with its efforts under the National Program, STD Research Corporation has also carried out related contracts for analysis of MHD systems and components with several industrial organizations, including Electric Power Research Institute, Southern California Edison, Reynolds Metals, Gilbert Associates, TRW, and others.

DESCRIPTION OF WORK

The scope of the work under Contract DEN3-202 includes tasks for code development/modification, data analysis, performance analysis, topical analysis, code documentation and delivery, and reporting. Under the data analysis task, STD Research Corporation is to critically compare the results of experimental tests with detailed simulations. The performance analysis task consists of simulations of configurations, designs, scales, and operating conditions specified by NASA. The topical analysis task includes phenomenological analysis to investigate specific phenomena that occur within the MHD topping cycle. Topical analyses also include comparative analyses efforts to compare the results of calculations of particular configurations by codes of differing complexity or differing critical assumptions.

Contract DEN3-202 is a Task Order type contract. Within the above scope of work, the following Task Orders have been issued:

<u>Task Order 1</u>: Contract Intiation and Preliminary Tasks

(1) Initiate code reactivation

(2) Maintenance of codes

(3) Simulations of the AEDC/HPDE incorporating estimated wall temperature distributions

(4) Publications.

<u>Task Order 2</u>: Contract Intiation and Preliminary Tasks

(1) Detailed Work Plans

(2) Initiate interelectrode breakdown analysis in the AEDC/HPDE

(3) Initiate computer terminal equipment activation

(4) Initiate NASA-specified ETF channel evaluation

Task Order 3: Completion of Software/Hardware Activation

Task Order 4: Code benchmark on NASA/Ames CDC 7600

Task Order 5: Publications

Task Order 6: AEDC/HPDE Performance Simulations

(1) Transient Hall voltage suppression techniques
(2) HPDE diagonal operation
(3) Analysis and Simulations of the AEDC/HPDE Experimental Data
(4) Interelectrode Breakdown Phenomena

Task Order 7: Analysis of NASA-specified ETF Channel

Task Order 8: Experimental Data Analysis

(1) CDIF 1A1
(2) U-25 Bypass
(3) Avco Mark VI

Task Order 9: Linear/Nonlinear Stability Analysis for Large, Diagonally-connected Generators

Task Order 10: Annual Report

FIRST YEAR STATUS

Task Orders 1, 2, 3, 4, 5, 7, 8, and 9 have been competed. Task Orders 6 and 10 are active. Emphasis is being placed upon analysis of experimental data obtained in AEDC/HPDE tests MI-007-004 through MI-007-008.

Reduced funding levels since October 1981 have forced reassignment or layoff of several personnel originally dedicated to this project. Completion within the original cost estimates of those SOW tasks which have not been assigned by Task Orders is therefore doubtful. Month-to-month funding since October 1981 has precluded advantageous long-term agreements for computer and other services which were originally planned. Progress reported has been assured only by overworking personnel and exploiting the good will of computer service centers.

ACCOMPLISHMENTS

The work under Contract DEN3-202 has made practical engineering contributions to the operation of experimental flow trains, in particular to the AEDC/HPDE. In addition, the application of multidimensional computer simulations to high-power MHD systems, and the detailed comparison of these simulations with data from well-diagnosed experiments, has improved understanding of fundamental mechanisms which govern high-interaction MHD system performance.

Publications. The work under contract DEN3-202 has resulted in five publications to date, Refs. [1] through [5].

Support of on-going Experiments. The following are some of the contributions to the AEDC/HPDE operation made by STD Research Corporation during the course of Contract DEN3-202:

(1) Transient Hall Voltage Suppression Methods. In Ref. [6] STD Research Corporation analyzed the Hall overvoltage during the HPDE startup and recommended that simultaneous injection of seed and fuel would mitigate the effect. This overvoltage caused some difficulties during the MI-006-XXX series of tests in

1979-1980. During the MI-007-XXX series of tests in 1981, the method of simultaneous seed and fuel injection was adopted and was apparently successful in reducing the start-up Hall voltages to acceptable levels at magnetic field strengths up to 3.1 T [7]. (For example, see the Hall voltage traces given in Fig. 1 for Run MI-007-006).

Prior to the MI-007-XXX test series, STD Research Corporation utilized transient analysis codes to evaluate external techniques for voltage transient suppression. These methods, which included various configurations of fuses and bleed resistors, may be useful as the experiment progresses to higher magnetic fields. Fig. 2 shows typical results for one such configuration.

(2) Voltage Drop Suppression. The incorporation of pyrolytic graphite electrode caps in the MI-007-XXX series of tests improved the HPDE performance by reducing electrode voltage drops. The magnitude of the voltage drop reduction and the performance improvement was predicted by STD Research Corporation [7]. Post-test simulations, using actual test conditions, yield satisfactory agreement between the measured and the computed voltage drops (for example, see Fig. 3)

(3) Optimal Loading. Fig. 4 shows optimal loading as a function the peak magnetic field for the HPDE generator operating with pyrolytic graphite electrode caps. These STD computational data have assisted in the selection of load settings for the HPDE [7]. It was shown that for given operating conditions, the optimum load schedule is that which brings the downstream shock into the neighborhood of the generator exit (see Fig. 5).

(4) <u>HPDE Performance with Diagonal Connection.</u> The external diagonalization of the HPDE channel at 4 T operation with pyrolytic graphite electrodes was simulated with the STD multidimensional codes. It was concluded that, with the present channel geometry and with the planned diagonalization scheme, a significant reduction in perfomance would result from the significantly lower electrical conversion efficiency possible, even with optimum loading (see Fig. 6). Due to reduced efficiency, the flowfield in diagonal operation is markedly different than in Faraday operation (see Fig. 7), and it is likely that relofting would be required to improve diagonal performance.

Linear and nonlinear magnetohydrodynamic flow stability was investigated in the diagonalized HPDE up to peak magnetic fields of 6 T. Diagonal operation was found to be stable for all cases considered.

(5) <u>Interelectrode Breakdown</u>. A survey was made of axial current leakage through the plasma over the insulators. These calculations indicated that the threshold for significant current leakage occurs above 5 T operation when the entire electrode/insulator surface remains below 1800 K (Fig. 8A). Nonideal phenomena such as the magnetoaerothermal effect [2] may cause local temperature elevations over certain parts of the electrodes. In the case where such temperature elevations approach the core temperature, significant current leakage can occur even at peak magnetic field strengths of 3 T (Fig. 8B). Work is in progress to evaluate improvement in resistance to axial leakage by use of alternate insulator configurations.

Analysis of experimental data. Detailed measurements for AEDC/HPDE Runs MI-007-004 through MI-007-008 have been analyzed. Time periods during Runs MI-007-004, -006, and -007 were selected for simulation with STD Research Corporation multidimensional and time dependent codes. The time periods selected for Run MI-007-00-006 are indicated in Fig. 1.

Measurements for "experimental conditions," such as flow rates, loads, magnetic field distribution, etc., were utilized in the simulations wherever possible. For example, Fig. 9 compares the load schedule employed for the simulations of time period II of Run MI-007-006 with values inferred from measured currents and voltages at the instrumented electrodes. Where input data required for the simulations were not available from direct measurements, STD relied upon the best estimates from the experimental team.

Agreement between the global output parameters of the experiment and the computations is satisfactory and consistent with the uncertainties in the input data. Fig. 10 compares the computed power output for each of the runs simulated with the nominal experimental values. Fig. 3 compares the total electrode voltage drops computed and deduced from pegwall voltages in simulation time period II of Run MI-007-006.

Because global power output or total voltage drops are not primary measurements of the experiment (they must be inferred from many other measurements), they are not necessarily the best measures of the accuracy and validity of the codes. A more sensitive and reliable indicator is the generally satisfactory agreement between the computed and measured internal distributions of the primary measurements, such as the local current per electrode, shown for example in Fig. 11 for simulation time period II of Run MI-007-006.

The internal structure of the HPDE flowfield is revealed to some extent by the available measurements. STD Research is in the process of comparing the results of its most advanced multi-dimensional codes to these detailed measurements to determine the interaction level at which truly three-dimensional effects begin to dominate the performance of the device.

Two manifestations of high interaction-related phenomena have been identified in the data at 2 to 3 tesla. These are: (1) strong cathode-to-anode asymmetry in the measurements of the exit total pressure profiles, and (2) significant cathode-to-anode asymmetry in the pegwall voltage distributions.

Figure 12 illustrates the dependence of the exit total pressure asymmetry on magnetic field strength by comparing the time histories of the total pressure measurements for tests with magnetic field strengths of 2.1, 2.8, and 3.1 T. The following observations are made: (1) The total pressure profiles are skewed toward the cathode. (2) The flatness of the anode boundary layer appears to indicate separation at magnetic fields of 2.8 and 3.1 T. (3) Increasing magnetic field strength appears to cause the cathode boundary layer to fill out. Fig. 13 presents a summary of these trends.

Figure 14 displays the pegwall voltage measurements as a function of time for the same three tests. The effect of wall heating in diminishing electrode voltage drops is apparent. In addition, the predominance of the anode voltage drop over the cathode drop is obvious in all cases.

These observations are consistent with the onset of the magnetoaerothermal effect described in Ref. [2] and with predictive calculations at higher interaction than the tests to date. Fig. 15 shows a typical axial and secondary flow field in the HPDE operating at 5 tesla. It may be seen that the anode boundary layer contains a local region of strongly decelerated

flow. This region is caused by interaction between secondary flows, which redistribute the flowfield, and the distribution of current. A more complete explanation is provided in Ref. [2].

The axial development of the total pressure field in Fig. 16 exhibits the transition between conventional boundary layer profiles and distributions distorted by the MHD forces. In Fig. 17 an enlargement of the 3 m and 4 m profiles is sectioned to reveal the mid-electrode profiles of stagnation pressure. These computed values are strikingly similar to the experimental data.

Direct comparison between HPDE pegwall voltage data and the results from advanced three dimensional codes has been carried out for Run MI-006-014 [1]. The voltage drop asymmetry, shown in Fig. 18, is quite apparent in both data and the computation. The qualitative similarity to the data in Fig. 14 is obvious.

The importance and the possibly deleterious effects of such asymetries are described in Refs. [2] and [3]. Suffice it to say that the HPDE is entering a regime of interaction sufficiently high to expect significant distortions of the flowfield by MHD forces. It is a regime where few open cycle MHD experiments have been carried out. Figure 19 shows the levels of interaction of several cases studied during Contract DEN3-202 and its predecessors. These cases range from laboratory scale devices to full-scale commercial generators. Above 0.6 MJ/kg, all of the points are computations, rather than tests.

One experimentalist who has achieved high levels of MHD interaction has summarized his work as follows [9]:

> "Using an effective solid-fuel plasma generator, specific power output [and power density] of up to 0.6 MJ/kg and 500 W/cm^3, respectively, was generated. Further increasing these parameters (and accordingly at (sic) the coefficient of enthalpy extraction) can be achieved only if the limiting effect of processes associated with strong interaction are suppressed. The nature of these processes is not yet fully understood, thus it is necessary to continue the study of these phenomena."

REFERENCES

[1] Vetter, A.A, Maxwell, C.D., Swean, T.F., Demetriades, S.T., Oliver, D.A., and Bangerter, C.D., "The STD/MHD Codes: Comparison of Analyses with Experiments at AEDC/HPDE, Reynolds Metal Co., and Hercules, Inc.," AIAA 19th Aerospace Sciences Meeting, St. Louis, MO, Paper No. AIAA-81-0173, January 1981

[2] Demetriades, S.T., Oliver, D.A., Swean, T.F., and Maxwell, C.D., "On the Magnetoaerothermal Instability," AIAA 19th Aerospace Sciences Meeting, St. Louis, MO, Paper No. AIAA-81-0248, January 1981

[3] Maxwell, C.D., Swean, T.F., Jr., Vetter, A.A., Crouse, R.D., Oliver, D.A., Bangerter, C.D., and Demetriades, S.T., "Three-dimensional Effects in Large Scale MHD Generators," AIAA 14th Fluid and Plasma Dynamics Conference, Palo Alto, CA, Paper No. AIAA-81-1231, June 1981

[4] Vetter, A.A., Maxwell, C.D., and Demetriades, S.T., "The STD/MHD Codes: Comparison of Analyses with Experiments," AIAA Paper 80-0024, AIAA 18th Aerospace Science Meeting, Pasadena, CA, 14-16 January 1980; to be published in J. Energy, 1982

[5] Maxwell, C.D., Demetriades, S.T., Oliver, D.A., Vetter, A.A., Swean, T.F., "Scale-up of Advanced MHD Generators," AIAA 18th Aerospace Sciences Meeting, Pasadena, CA, Paper No., AIAA-80-0168, January 1980; to be published in J. Energy, 1982

[6] STD Research Corporation, "Analyses of Critical Transient Phenomena in the AEDC HPDE," Report FE-2243-17 prepared under U.S. Department of Energy Contract EX-76-C-01-2243, May 1978

[7] Arnold Engineering Development Center, "MHD High Performance Demonstration Experiment," Quarterly Progress Report for April - June 1981, prepared under Interagency Agreement No. ET-79-I-01-2895, August 1981

[8] Maxwell, C.D., Demetriades, S.T., Oliver, D.A., Vetter, A.A., Swean, T.F., "High Interaction Effects in Large Experimental and Commercial Scale MHD Power Trains," Proc. 7th International Conference on Magnetohydrodynamic Electrical Power Generation, Massachusetts Institute of Technology, June 1980

[9] Velikhov, Ye.P., Volkov, Yu.M., Zotov, A.V., Matveyenko, O.G., and Yakyushev, A.A., "Factors Influencing The Self-Excitation of Pulse Type MHD Generators," Proc. 6th International Conference on Magnetohydrodynamic Electrical Power Generation, Vol. VII, p. 141, Washington D.C., June 1975

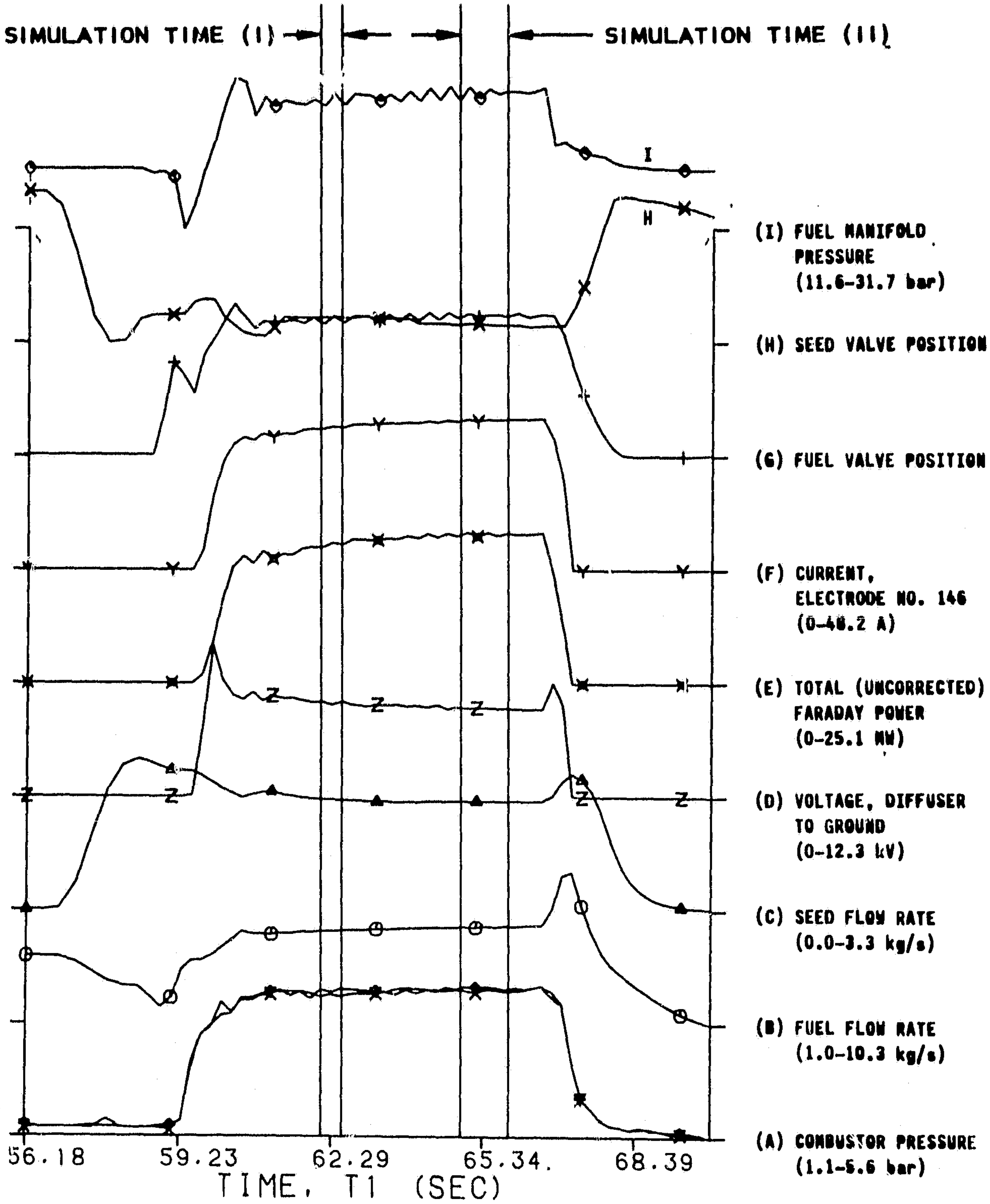

Fig. 1. Experimental data from HPDE Run MI-007-006 for key startup and shutdown variables as a function of T1.

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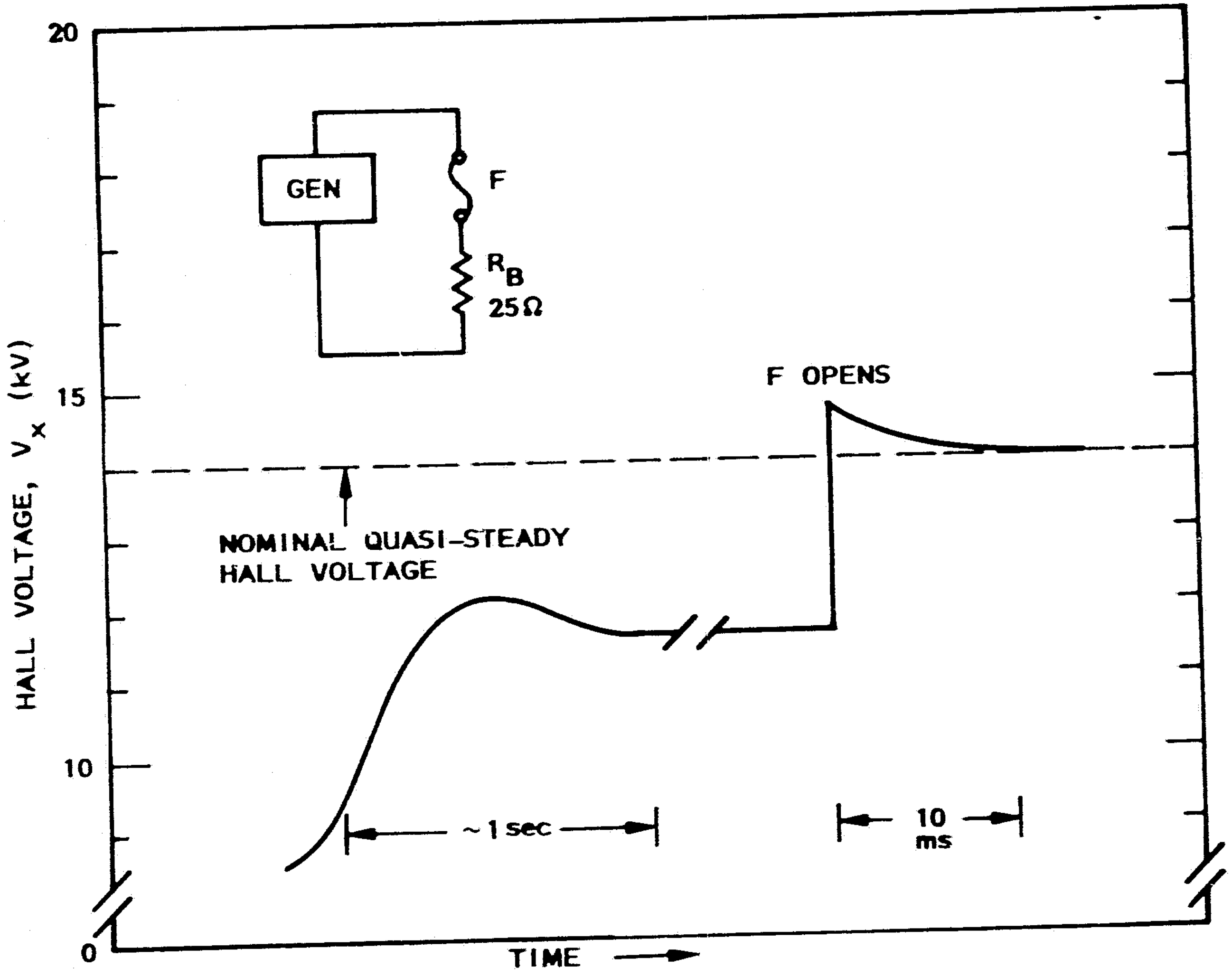

Fig. 2. Hall voltage history with a 25 ohm bleed resistor in series with a fuse.

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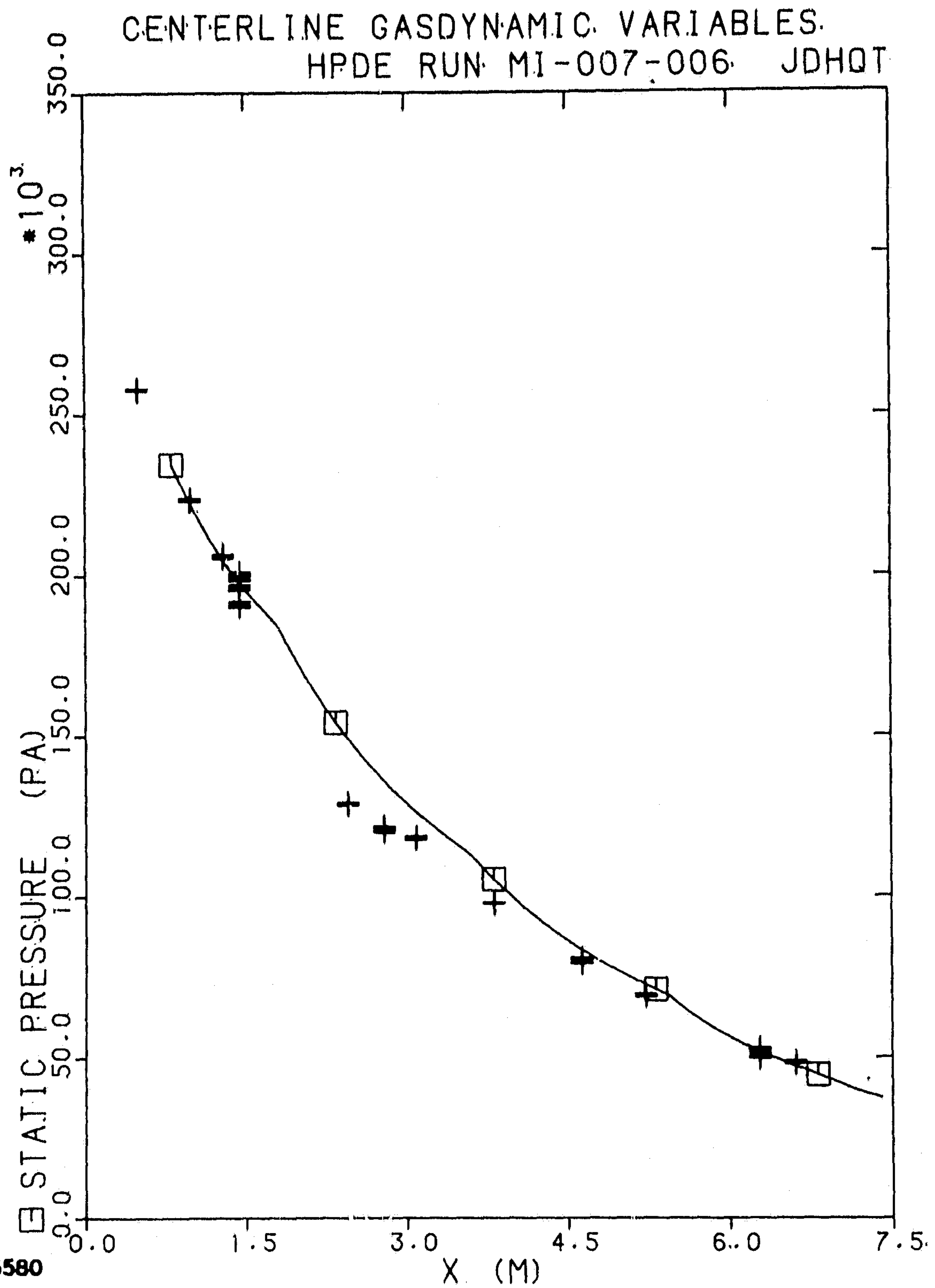

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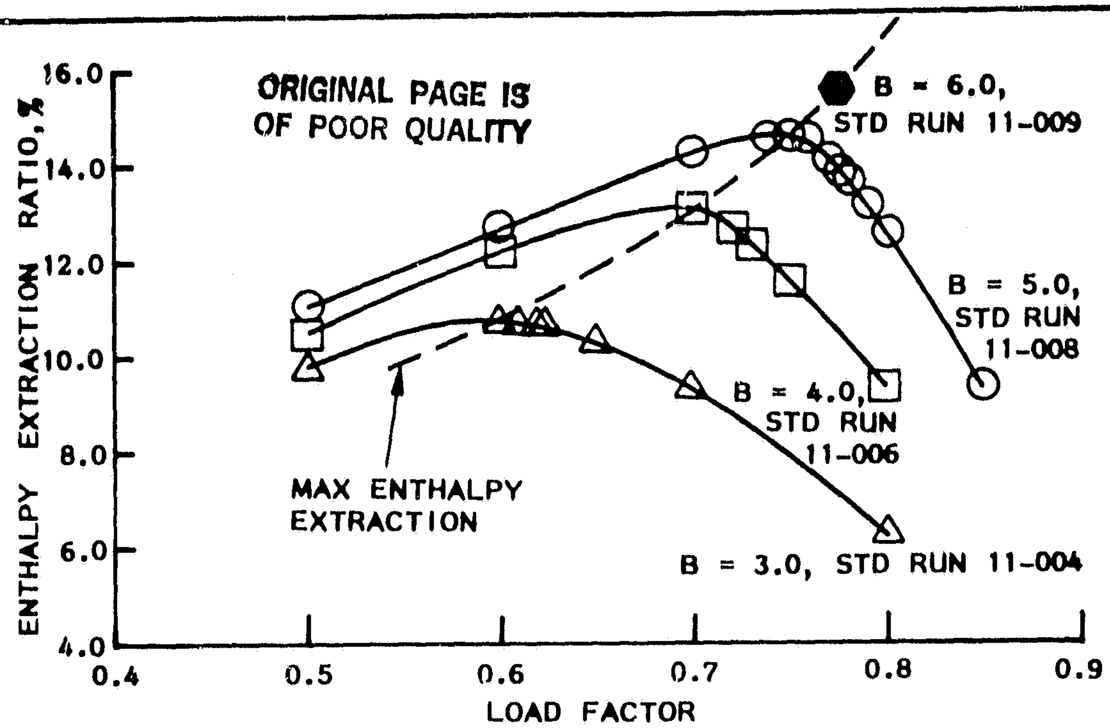
Fig. 3. Comparison of experimental data from HPDE Run MI-007-006 for 6.08 $\leq T_2 \leq$ 7.08 with static pressure calculated by Q3D computation 11-071.



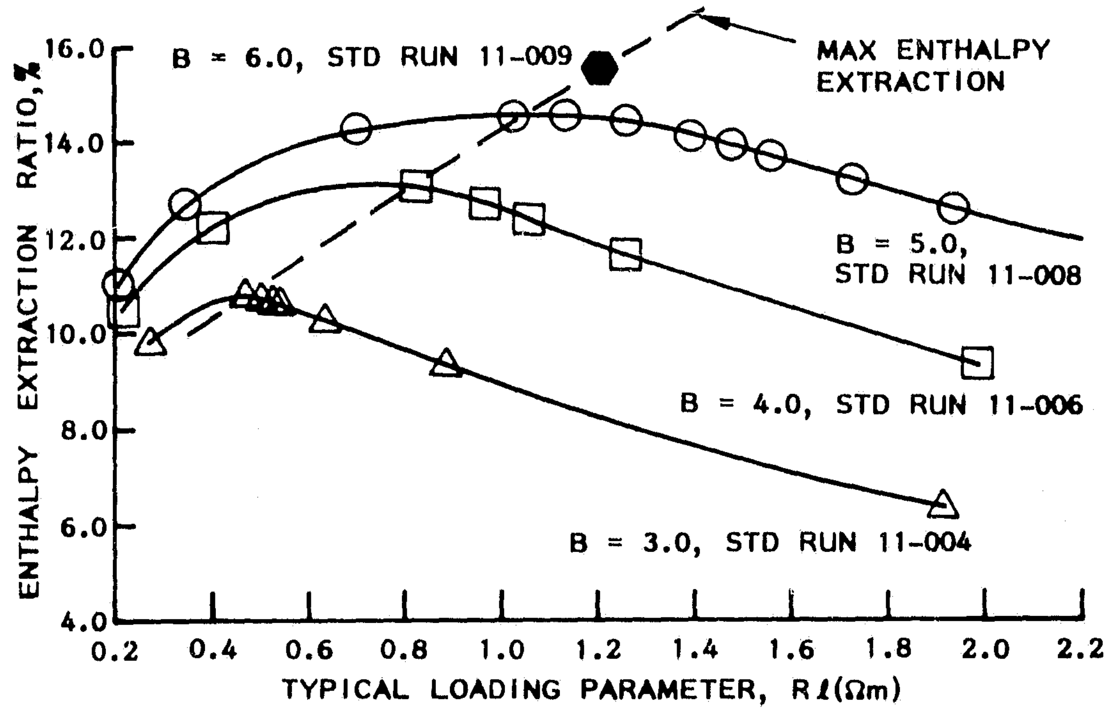


Fig. 4 . Variation of enthalpy extraction ratio with load factor and typical loading parameter for conditions of HPDE run 006-014 and pyrolytic graphite electrode wall temperatures defined at 10 seconds with no exothermic surface reactions considered.

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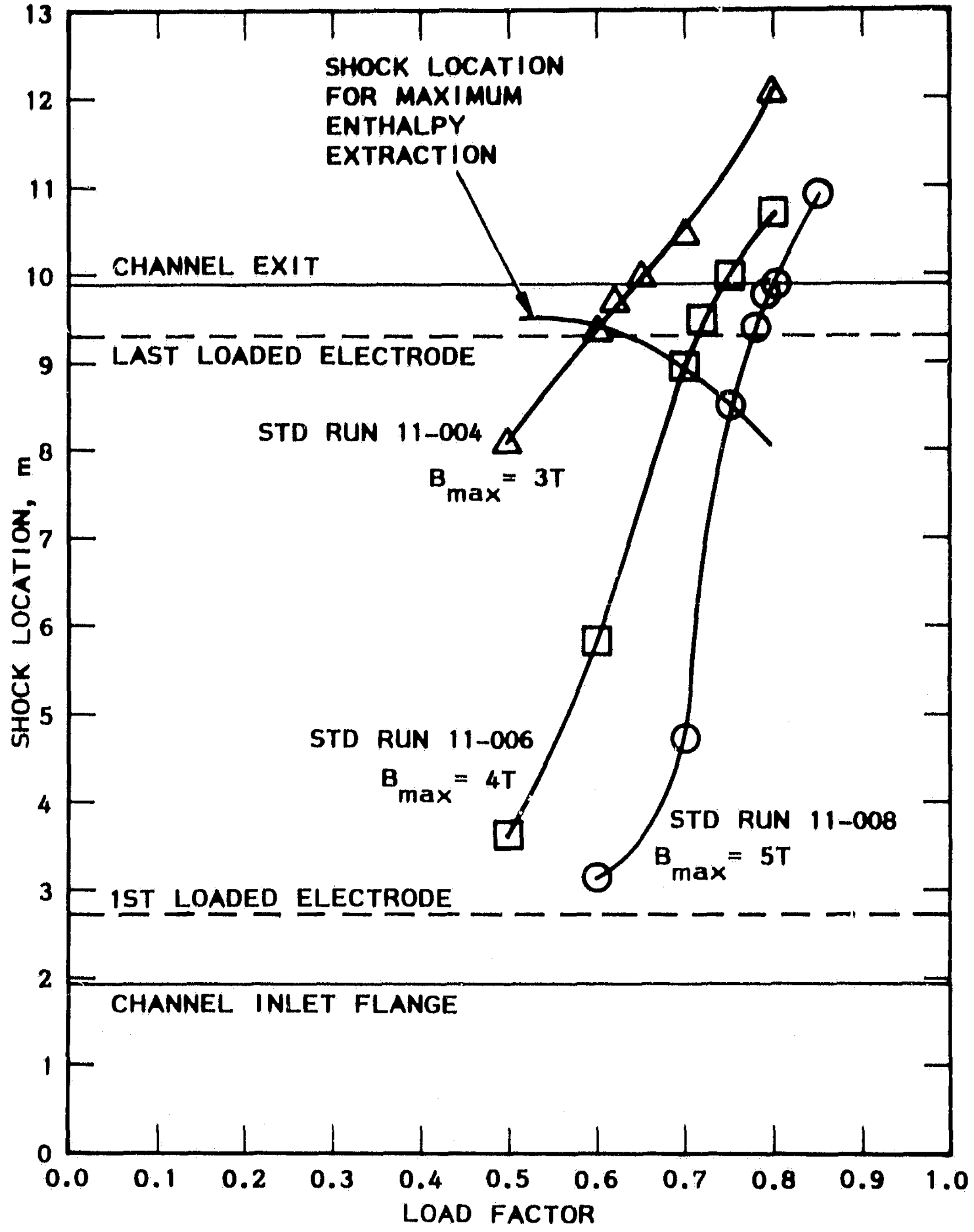

Fig. 5. Shock location for different load factors and magnetic field strengths for the AEDC/HPDE channel with conditions of HPDE run 006-014 and pyrolytic graphite electrode wall temperatures defined at 10 seconds with no exothermic surface reactions considered.

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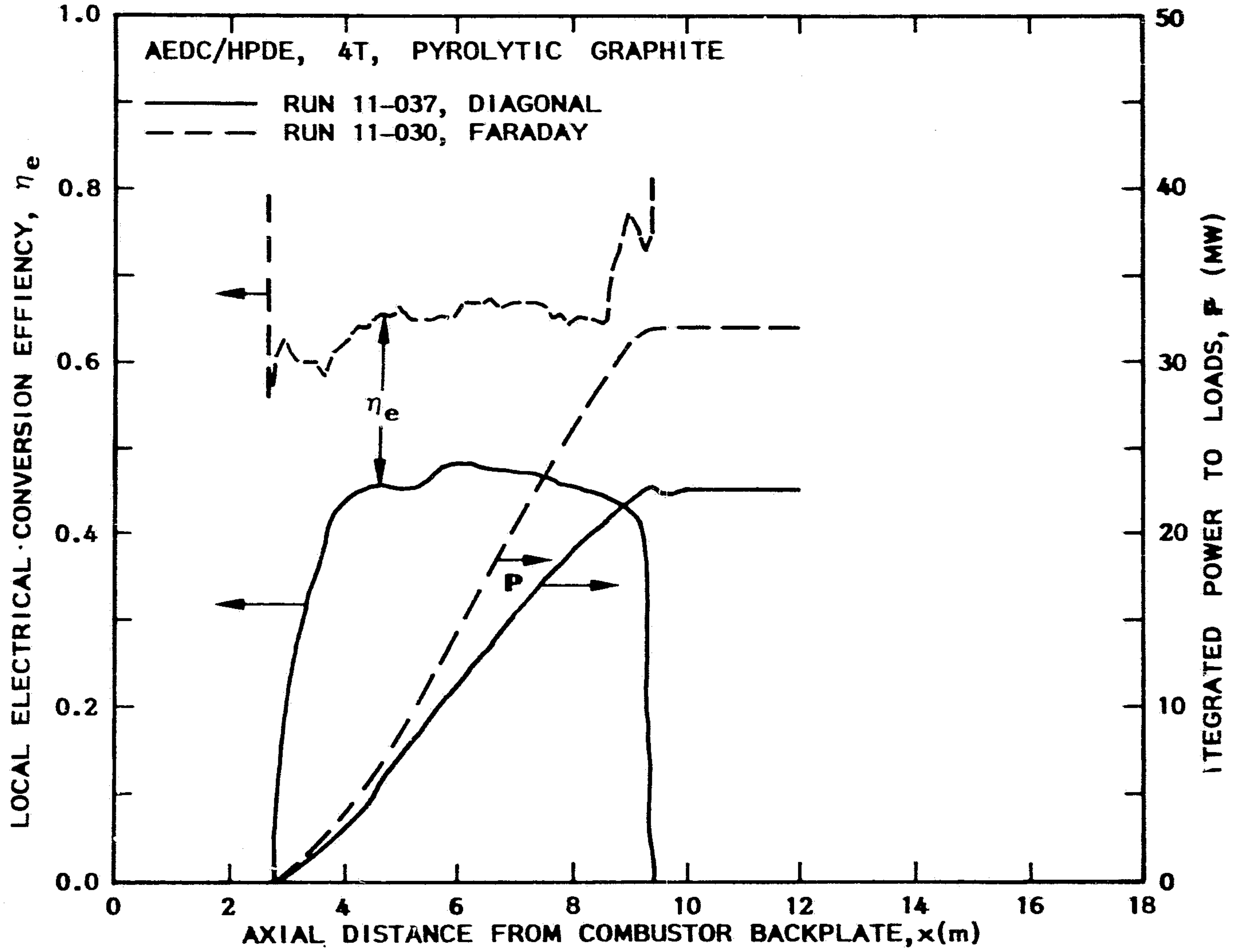

Fig. 6. Comparison of the local electrical conversion efficiency and integrated power output in diagonal and Faraday simulation of the HPDE with 4T peak magnetic field, Run 006-014 flow conditions, and pyrolytic graphite electrodes in sections 2-4.

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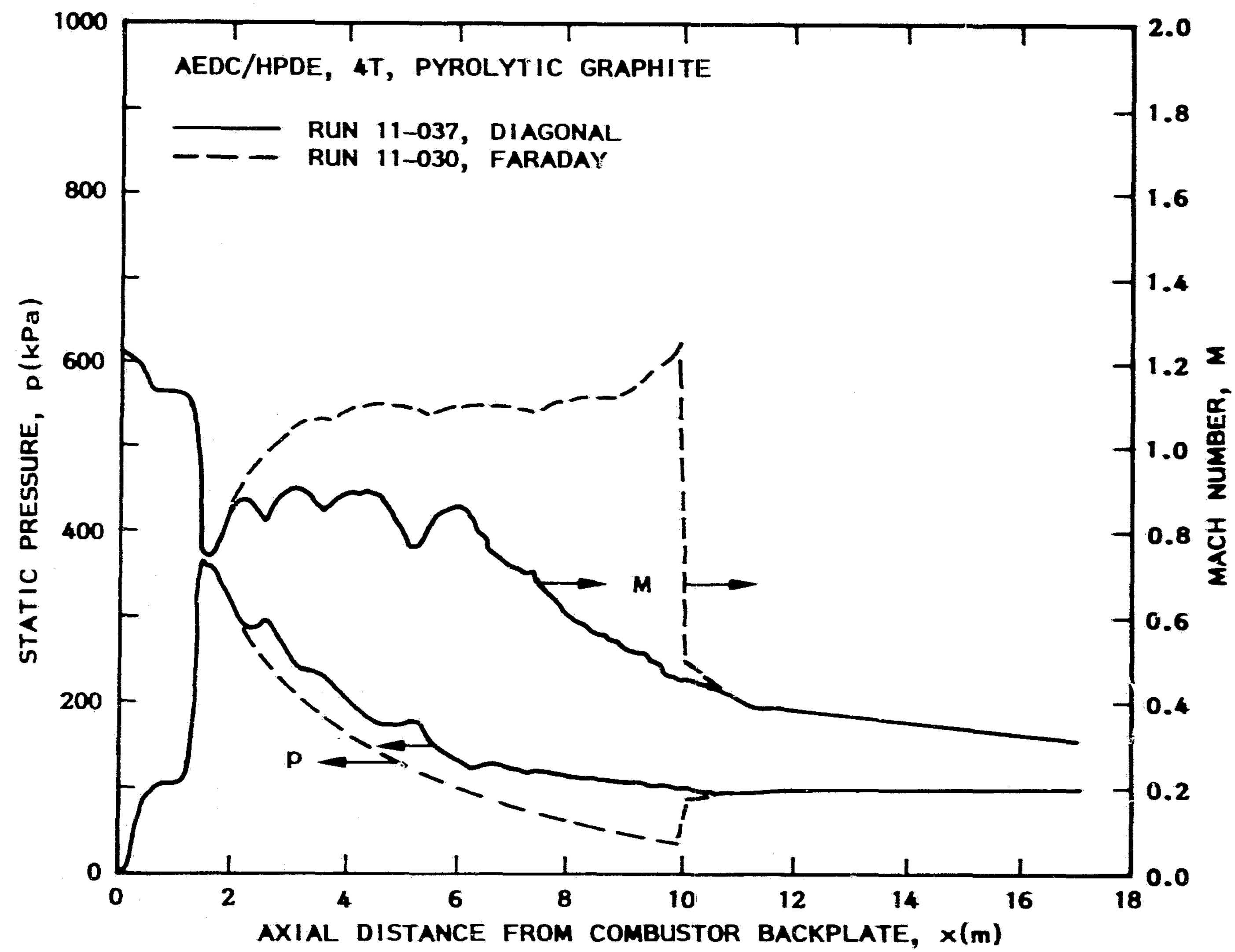

Fig. 7. Comparison of the axial variation of static pressure and Mach number in diagonal and Faraday simulations of the HPDE with 4T peak magnetic field, Run 006-014 flow conditions and pyrolytic graphite electrodes in sections 2-4.

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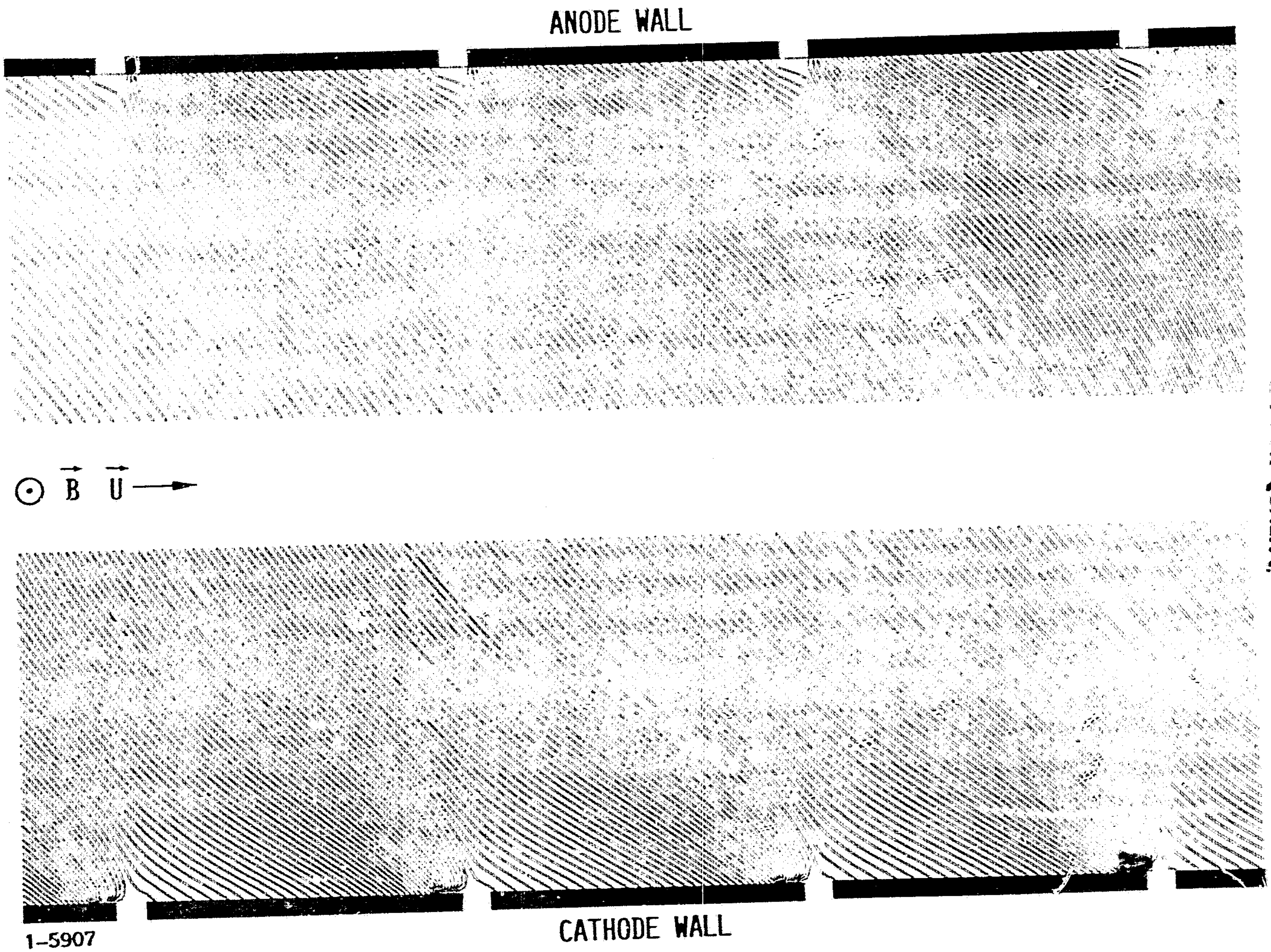

Fig. 8. Streamlines of the current density in the near-electrode region of the AEDC/HPDE 2.79m downstream from the inlet flange. Magnetic induction 5 T; effective wall temperature 1800 K.

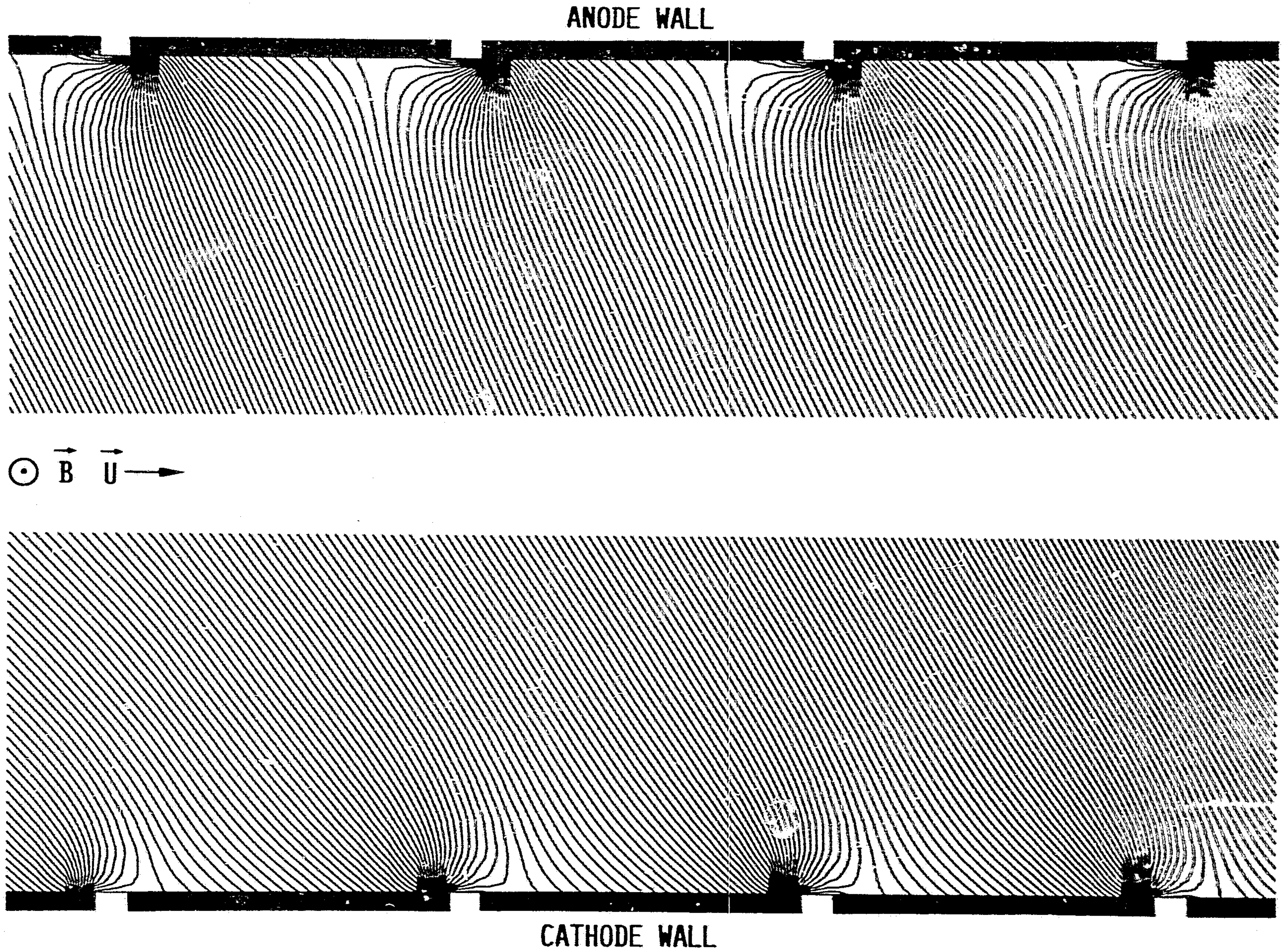

Fig. 9. Streamlines of the current density in the near-electrode region of the AEDC/HPDE 2.79m downstream from the inlet flange. Magnetic induction 3 T; effective wall temperature 3000 K.

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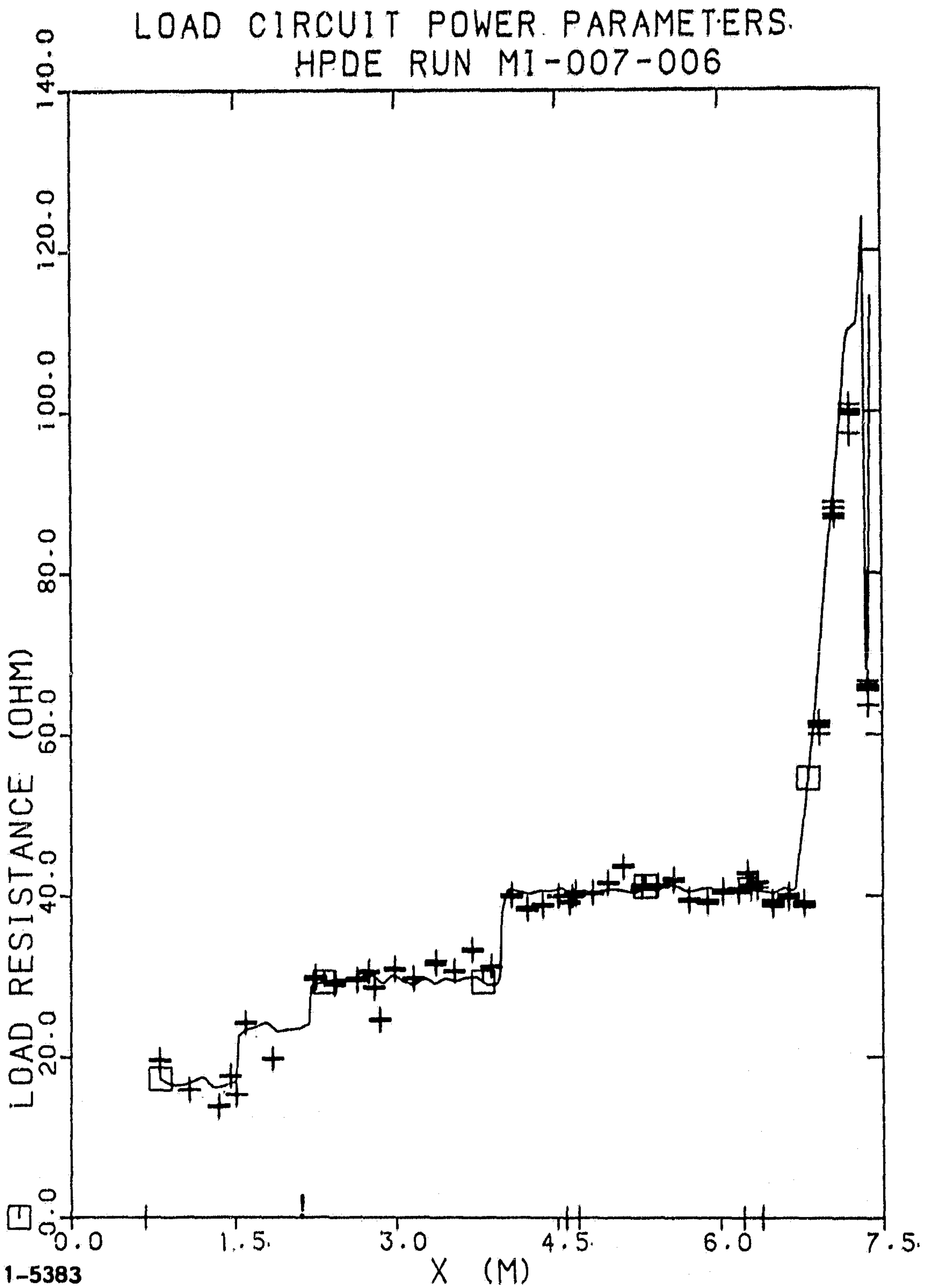

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Fig. 10. Comparison of the axial distribution of load resistance used for STD simulations with the experimental values measured for period II of HPDE Run MI-007-006.

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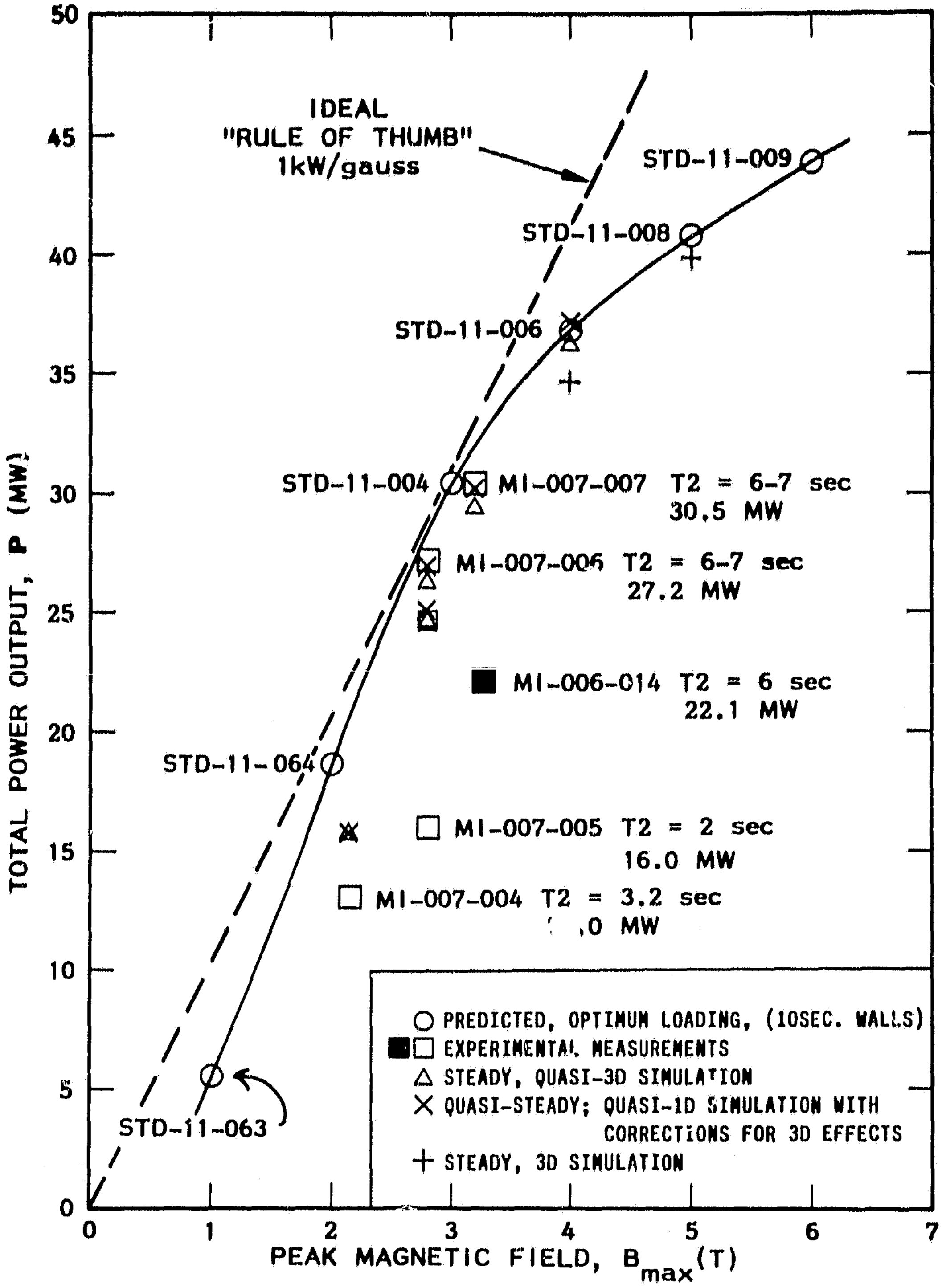

Fig. 11. Comparison of computed and measured total power output of the AEDC/HPDE generator channel. These are all either 3-D runs or runs corrected for 3-D effects.

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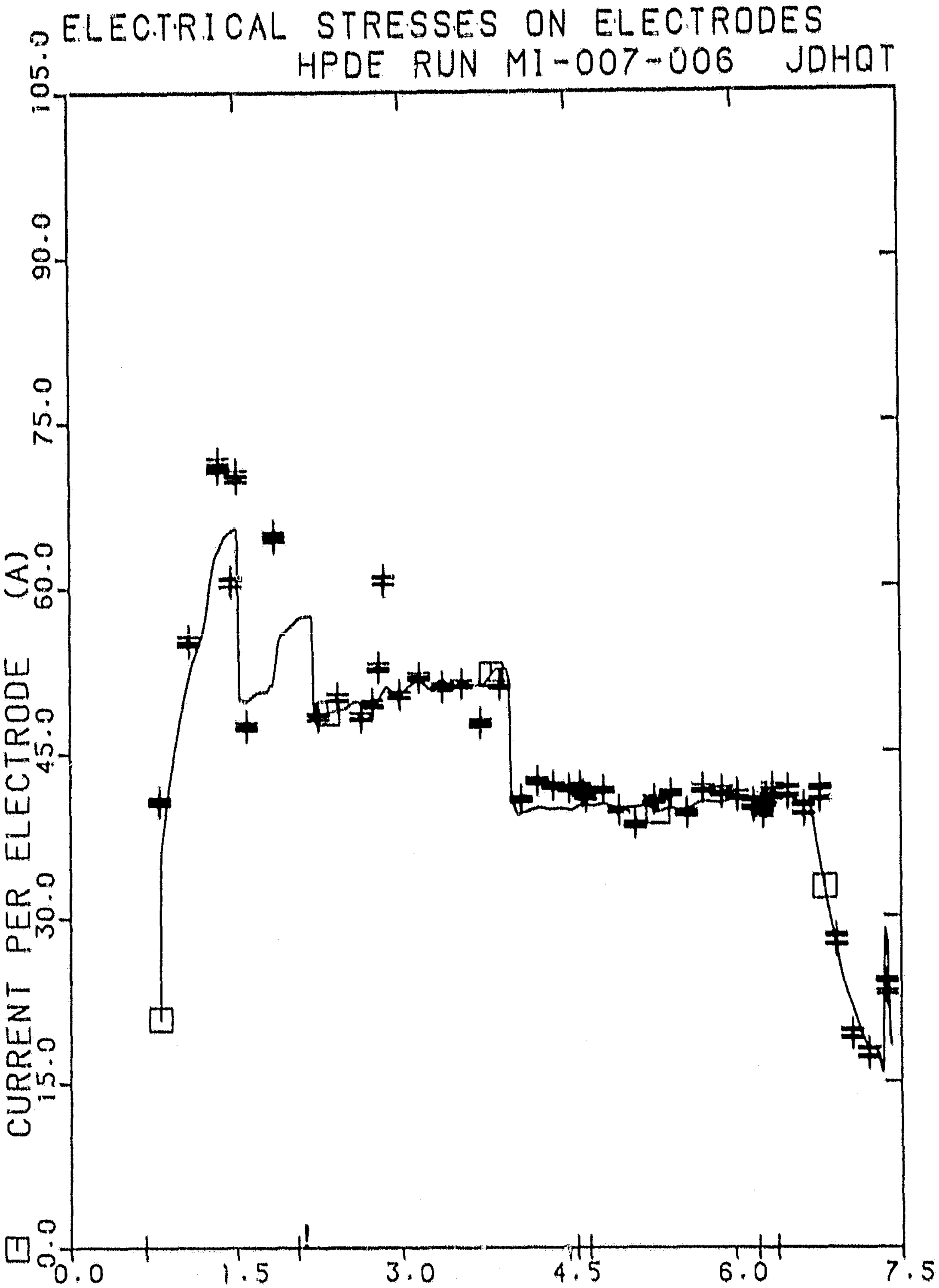

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Fig. 12. Comparison of experimental data from HPDE Run MI-007-006 for $6.08 \leq T_2 \leq 7.08$ with current per electrode calculated by Q3D computation 11-071.

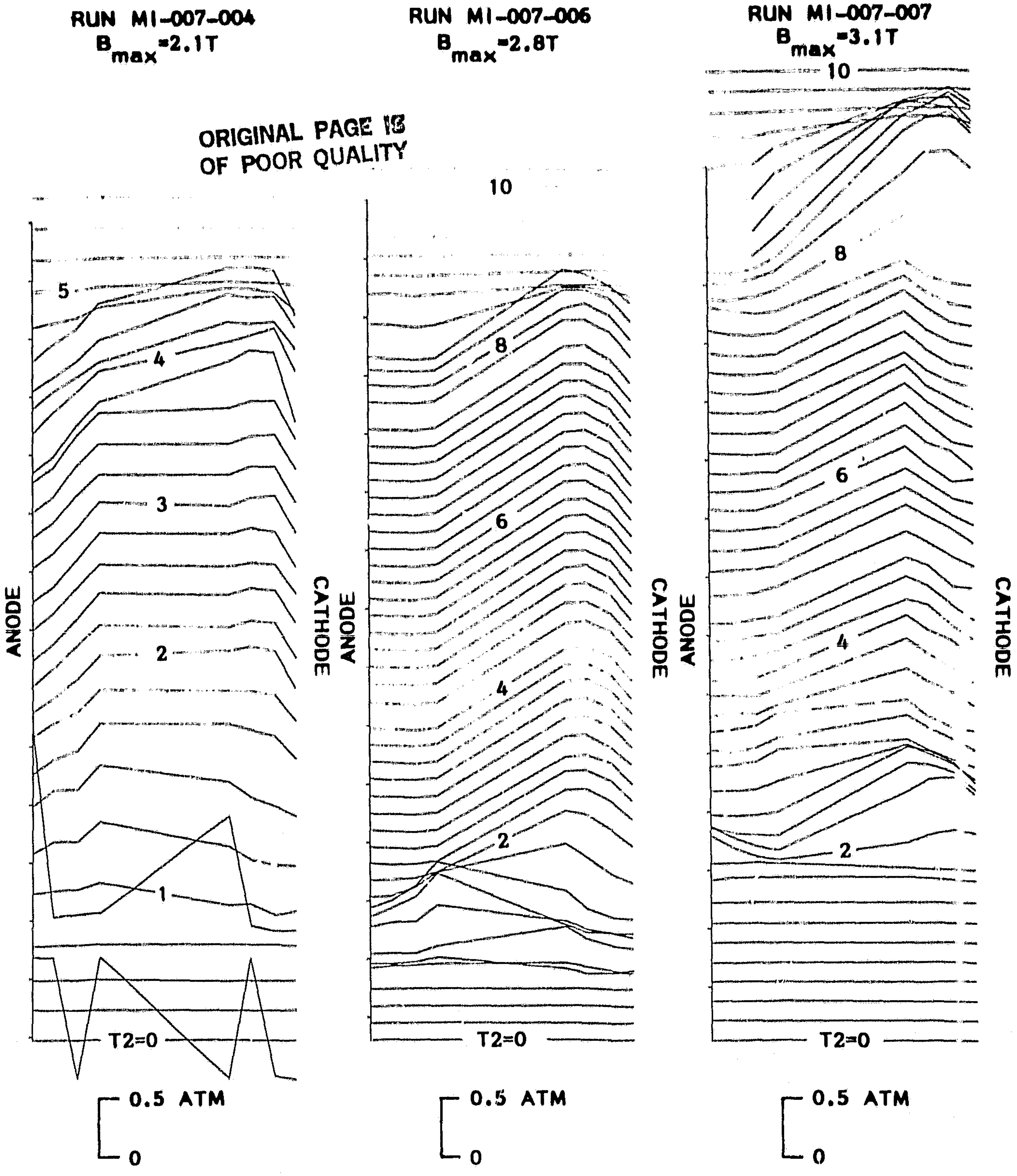

Fig. 13. Time evolution of measured total pressures away from the center of the electrode walls at a probe location approximately 1 m downstream of the last loaded electrode in the AEDC/HPDE. Numbered profiles indicate time in seconds after fuel valve opens. Vertical pressure scale is approximately 0.5 atm/cm. Typical wall values are 0.7 atm.

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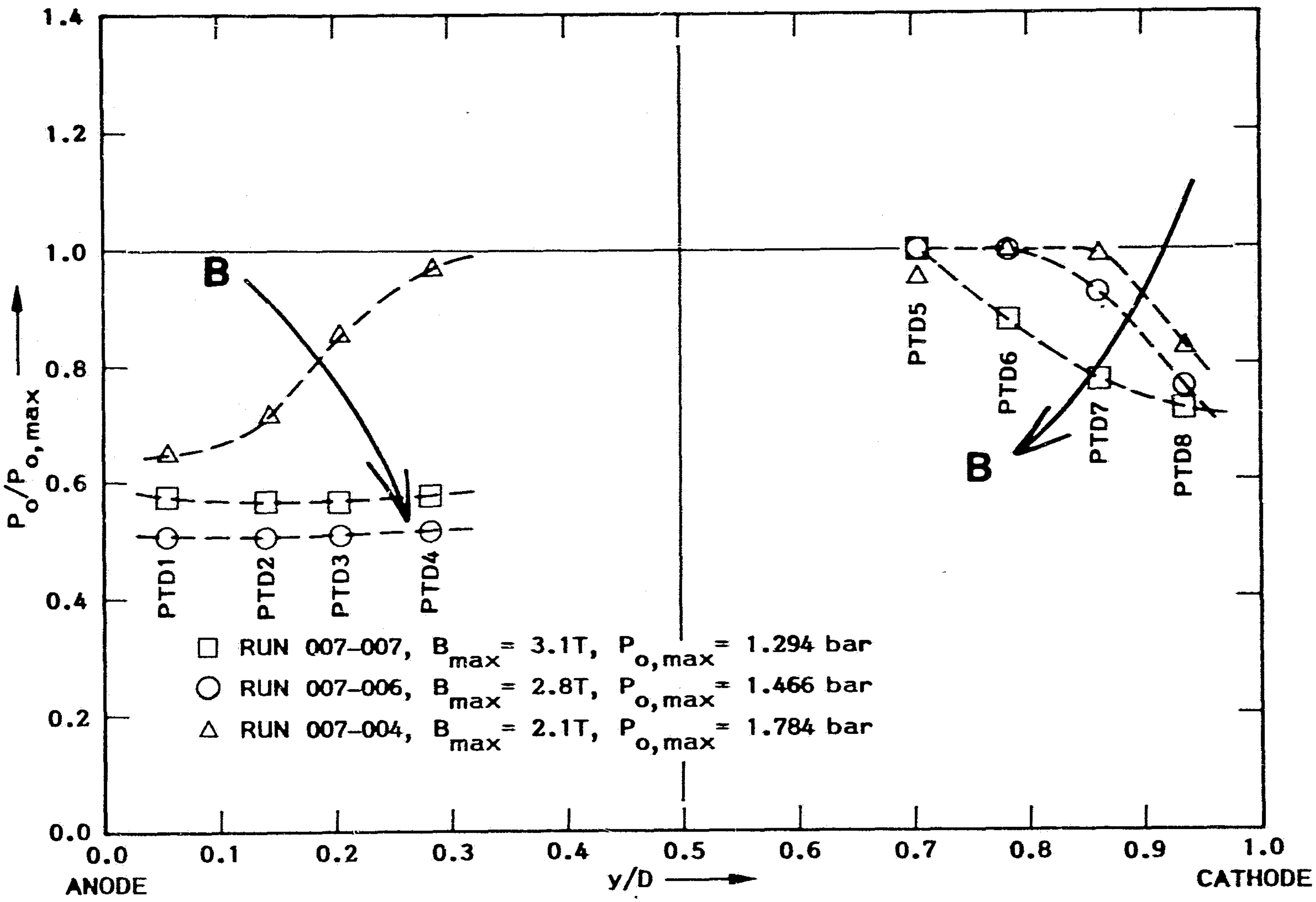

Fig. 14. Experimental values of the total pressure as a function of transverse distance and magnetic field strength in the diffuser at 9.73 m (from the inlet flange).

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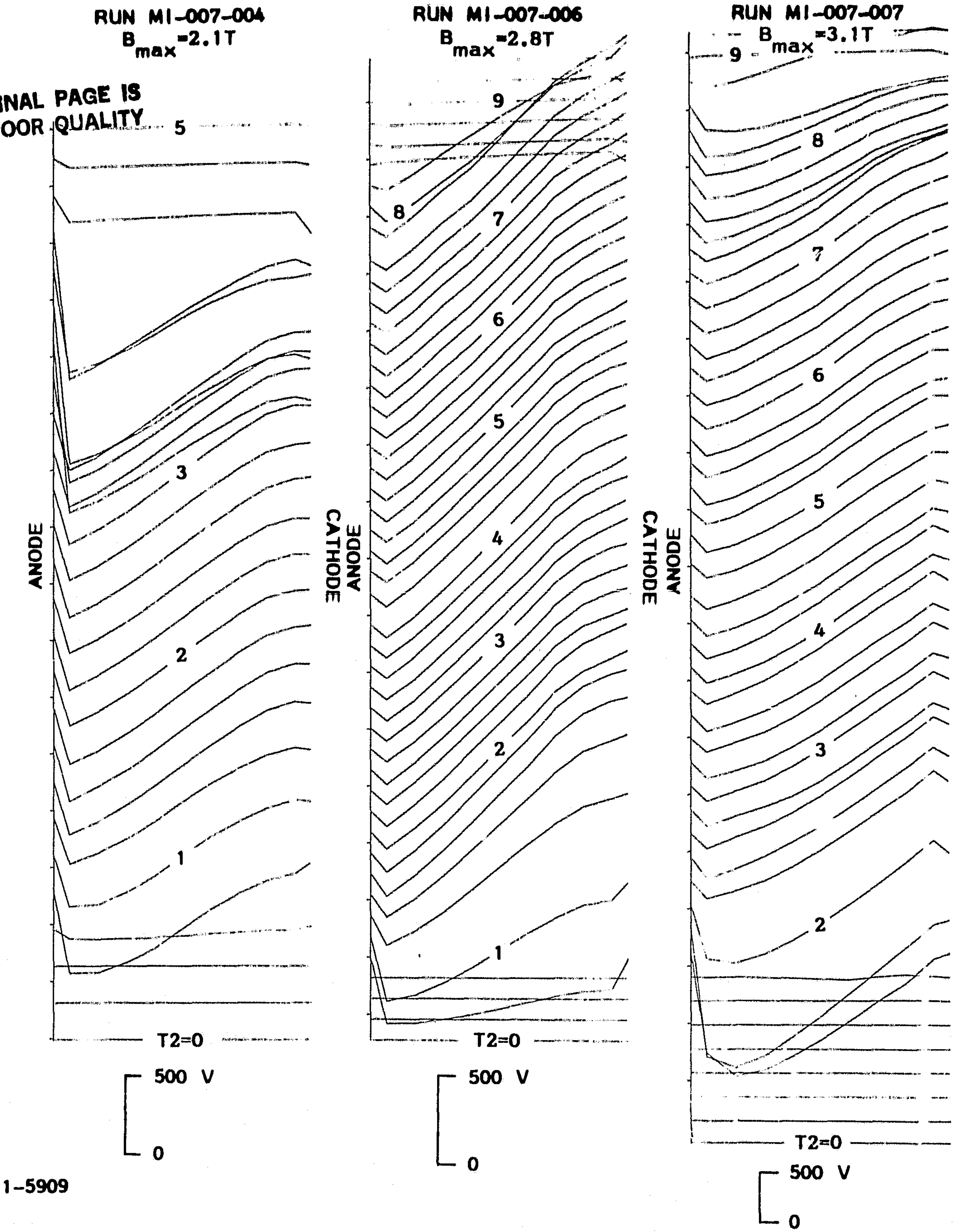

Fig. 15. Time evolution of measured pegwall voltages at the station x = 1.47 m downstream of the inlet flange in the AEDC/HPDE generator. Numbered profiles indicate time in seconds after fuel valve opens. Different vertical voltage scales are indicated beneath the data for each run.

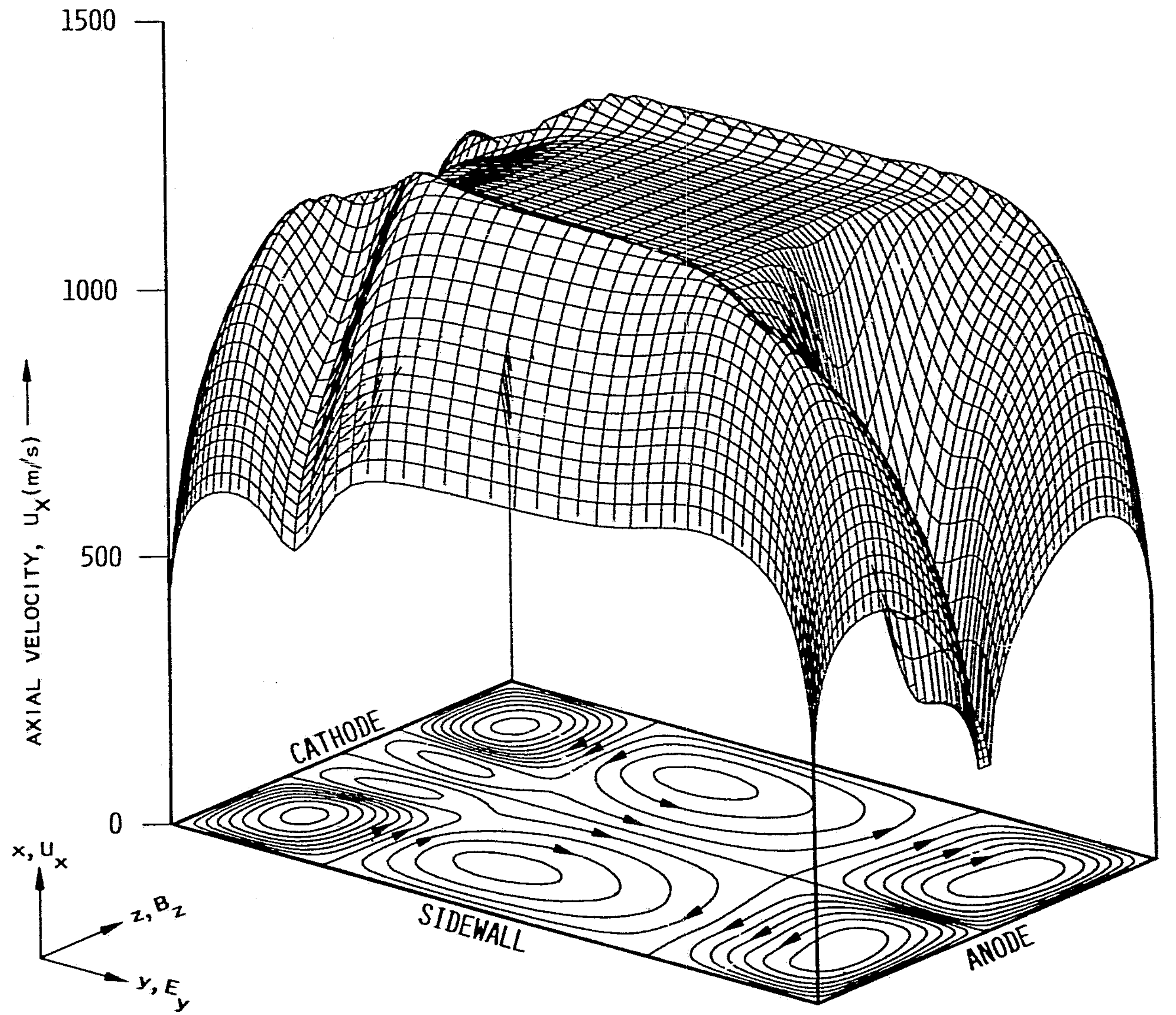

Fig. 16. The axial velocity magnitude and streamlines of the vortical component of the secondary flow velocity at x = 4m downstream from the first loaded electrode in the AEDC/HPDE. B_{max} = 5 T, $\dot{m}$ = 52.5 kg/s, Rl = 0.8 ohm-m.

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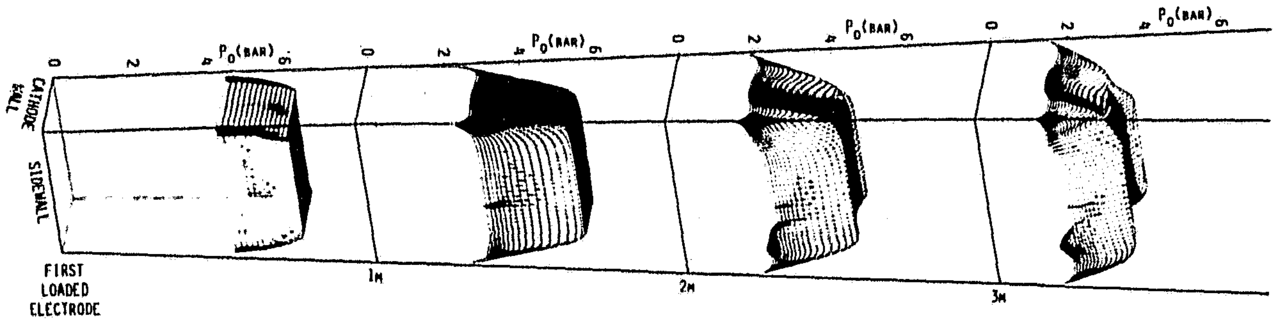

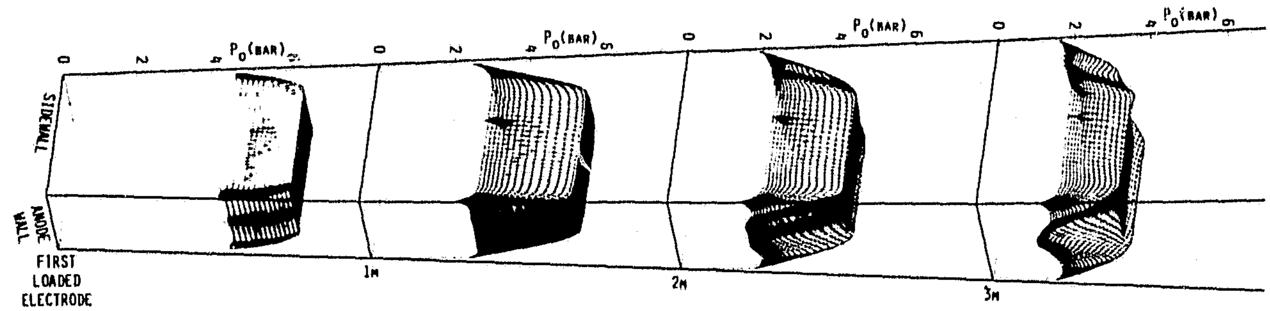

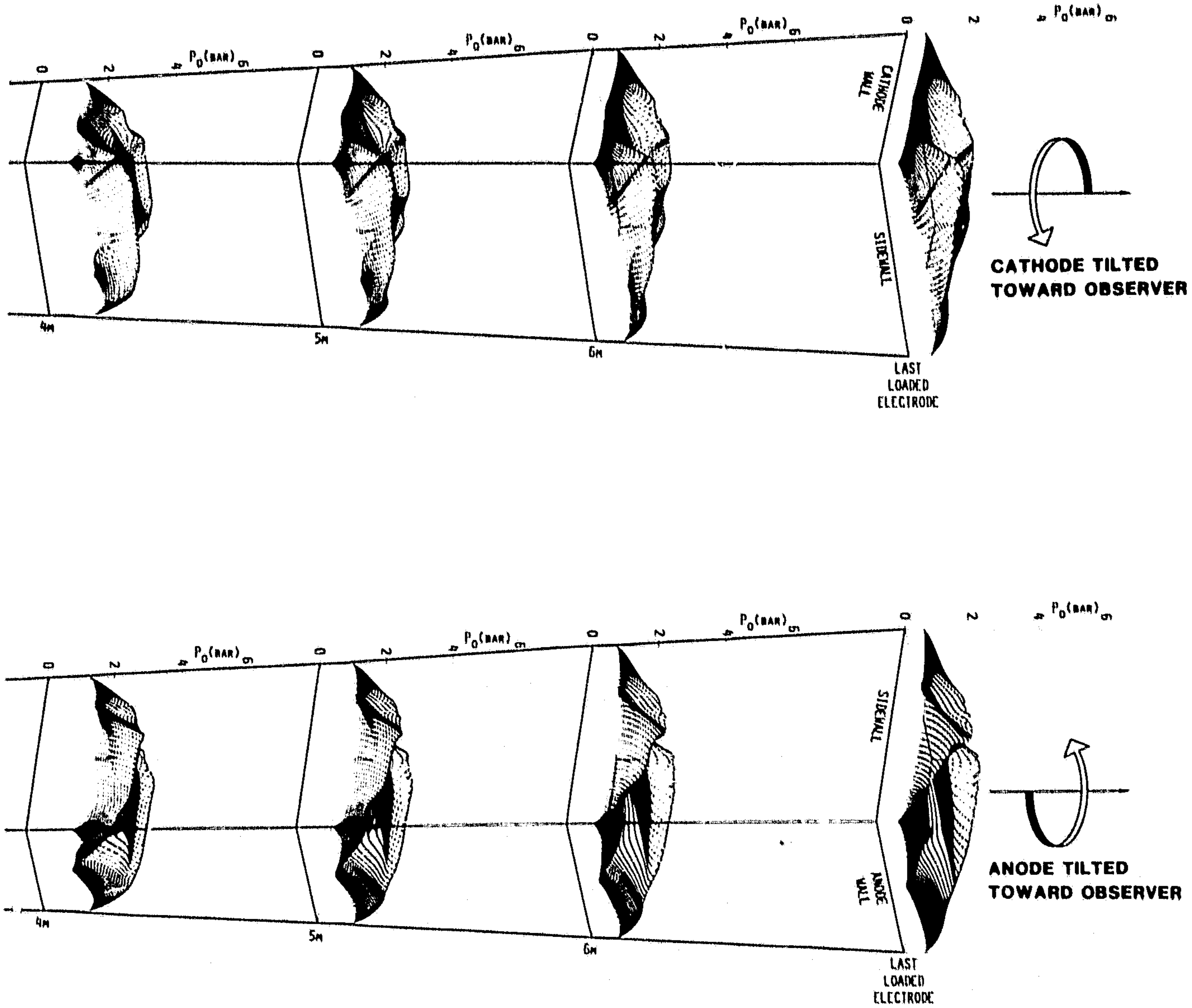

Fig. 17. Three dimensional development of cross sectional profiles in the AEDC/HPDE. Peak magnetic field is 5 T; mass flow rate is 52.5 kg/s; load parameter is 0.8 ohm-m, other conditions are as in HPDE Run MI-007-007.

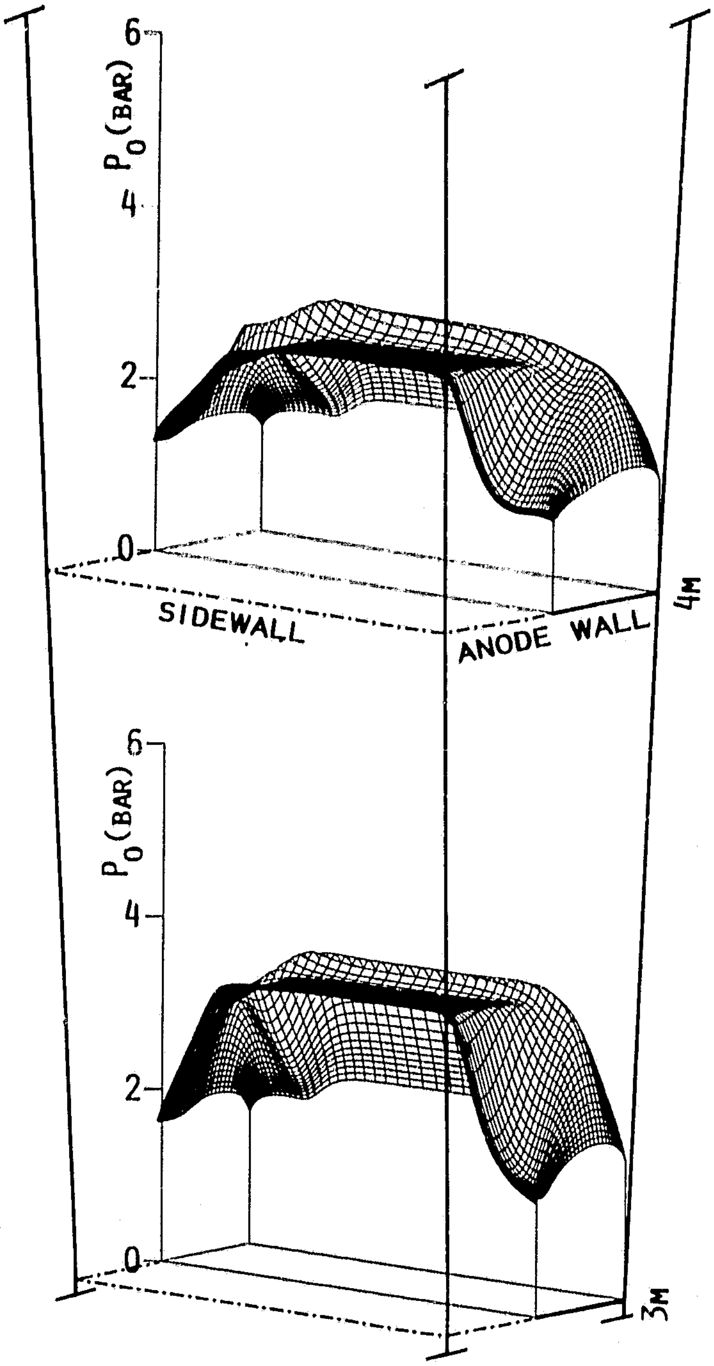

Fig. 18. Cut-away view of total pressure distribution in the cross section at stations x = 3 and 4 m from the first loaded electrode in the AEDC/HPDE. Peak magnetic field is 5 T; mass flow rate is 52.5 kg/s; load parameter is 0.8 ohm-m; other conditions are as in HPDE Run MI-007-007.

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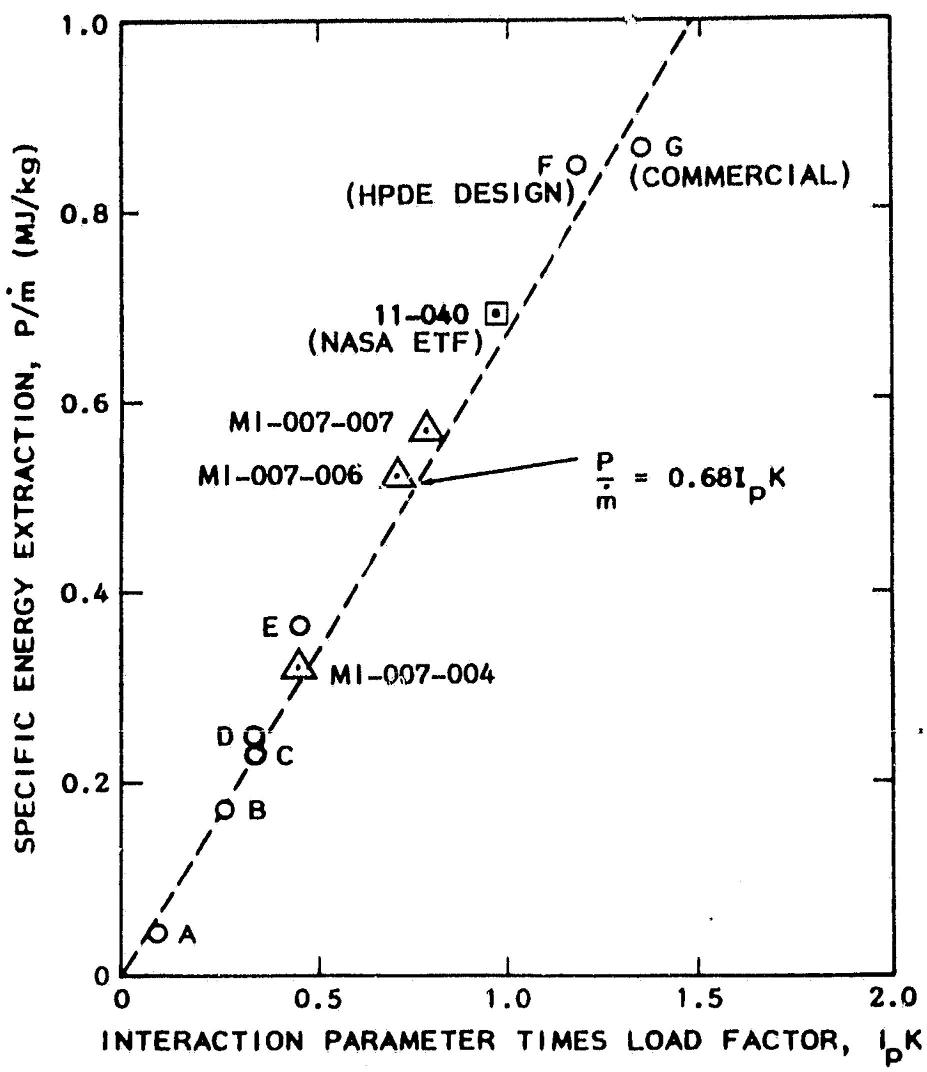

Fig. 19. Variation of specific energy extraction with the product of interaction parameter based on pressure and the generator electrical conversion efficiency. Circles denote Cases A-G of Ref. [8]. Square represents STD Computation 11-040 for the NASA-specified 500 MW (th) generator. Triangles represent STD simulations of recent AEDC/HPDE tests.

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